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MECHANISM ANALYSIS AND EVALUATION SYSTEM ON REGIONAL INTEGRATED ENERGY SYSTEM'S SYNERGIC DEVELOPMENT

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ABSTRACT

Energy structure is gradually transforming from a traditional coal-based structure to a diversified supply model in China, forming a multi-wheel drive, associated and interactive energy supply system. In this context, the integrated energy supply system will have a profound impact on the traditional energy planning, operation, management and other external systems. Therefore, it is necessary to research the connotation and characteristics of regional integrated energy systems, and to deeply analyze the interactions and mechanisms among energy subsystems. This paper establishes a system of comprehensive benefit evaluation indicators in four dimensions of basic function, clean development, energy security and energy efficiency, which are applied to the typical scenario of regional integrated energy development and provide a scientific tool of quantitative analysis and evaluation of synergic development of the regional integrated energy supply system.

Keywords: Regional integrated energy supply system, coordinated development, mechanism research, evaluation system.

1. INTRODUCTION

The energy transitions will drive solving many problems, such as lack of effective coordination among subsystems of energy supply, local imbalance and low energy efficiency. The conventional energy systems like electric power, thermal power, natural gas, etc. were separately planned, built, operated and maintained with no interrelation. Through mutually complementing and coupling of electric, heating, cooling and gas systems, the integrated energy supply system plays a significant role in improving the comprehensive efficiency of energy and infrastructure and promoting development and utilization of renewable energy [1,2]. Since the integrated energy supply system is in the initial stage of development, the study of benefit evaluation technology is important to the regional integrated energy supply system development in a medium and long run[3, 4].

The energy system consisting of various subsystems is a sophisticated and integrated system with complicated relations among different energy types and links. Meanwhile the energy system is impacted by factors like policy, economy, environmental protection, etc. The present study of synergetic evolution mainly concentrates on the bioscience sector and gradually extends to the sectors of communications, industry and energy[5-7]. The existing study of coordinated energy development mainly includes three aspects: firstly the study of supply and demand relations of different energy types and energy system coordination and optimization from the perspective of technology, secondly the study of energy system simulation from the perspective of planning[8-10], and thirdly the establishment of indicator system to evaluate the synergetic development from the perspective of performance[11-13]. However, few of them have probed into the integrated energy system or analyzed the impact mechanism of energy relations, and most of the evaluation indicators are qualitative instead of quantitative[14]. Therefore, the thesis conducts mechanism analysis of energy system relations and builds up the indicator system evaluating the extent of synergy that offers scientific methodology and tool to the development of integrated energy supply system.

2. CONNOTATIONS AND CHARACTERISTICS OF REGIONAL INTEGRATED ENERGY SUPPLY SYSTEM

2.1 Connotations and characteristics of regional integrated energy supply system

The integrated energy system refers to the multi-energy, full-chain integrated system formed after organic coordination and optimization of energy production, transmission and distribution (e.g. networks of electricity supply, gas supply, cooling/heating supply, etc.), conversion (e.g. CCHP unit, generator unit, boiler, air conditioner, heat pump, etc.), storage (storage of electricity, gas, heat, etc.) in the process of planning, construction, operation, etc. The regional integrated energy system is the geographical and functional manifestation of integrated energy system that integrates multiple types of energy within the region such as coal, petroleum, natural gas, electricity, heat energy, etc., and realizes coordinated planning, optimized operation, synergized management and mutual complementation of different energy subsystems.

The integrated energy system has the below characteristics:

1) In-depth integration: based on the networking integration of energy systems of different forms, the regional integrated energy system has multiple functions of energy production, transmission, conversion, storage, use, etc. and the integrated physical system realizes the in-depth integration between sectors and users.

2) Centralized planning: by advanced technology, equipment and system, the integrated energy supply system centralizes many energy resources, conducts general planning and dispatching for the objectives of cost minimization and benefit maximization, and to the greatest extent satisfies the diversified demand of stakeholders in the energy ecology system provided that safe and reliable energy supply is guaranteed.

3) Well structured: the regional integrated energy supply system is the restructuring of energy management organizational system of city and industrial park that requires clearly defined steps and structures in construction including identification of key areas of energy supply and well-structured implementation of energy planning, system management, fund raising.

4) Clean and low-carbon: the regional integrated energy system makes use of clean energy to replace traditional coal energy, controls carbon emission from the source and helps realize the clean and low-carbon objectives.

5) Economical and efficient: the synergetic coordination and control of systems may greatly improve the system flexibility and production and operation efficiency, reduce operation cost, impel efficient utilization of energy resource and thus uplift the economic benefit of energy construction investment.

2.2 *Characteristics of regional multi-energy complementation*

The analysis of coordination and complementation potentials of multi-energy output is the study of regulating characteristics of output equipment of cooling-heating-electric energy. The regulating scope of equipment is decided by the inherent characteristics of equipment and that of intermittent energy.

In terms of space, the smart energy system supply breaks the barrier of conventional model and regional restriction of separate energy supply. Various energy systems are mutually convertible and supportive via transformation equipment that offers additional energy supply approach and improves system reliability and cost efficiency.

In terms of time, the integrated energy system realizes peak shaving and valley filing by coordinated energy utilization. The joint energy supply changes the over-reliance on single energy in peak load period and thus increases the utilization rate of energy equipment.

In terms of method, the regional integrated energy supply system achieves distributed, flexible, economical and diversified co-supply of energy.

In terms of price, by comprehensive utilization of multiple energy, the smart energy system provides opportunity of conversion to and utilization of cleaner, cheaper and more efficient energy and effectively reduces total cost of system by optimized regulation and control.

3. MECHANISM ANALYSIS OF SYNERGETIC DEVELOPMENT OF REGIONAL INTEGRATED ENERGY SUPPLY SYSTEM

3.1 Mechanism of synergetic development of integrated energy supply system

The regional integrated energy system breaks the physical barrier of different energy systems like electricity, heating, cooling, gas, traffic, etc., realizes mutual complementation and integration of various energy and introduces plenty of renewable energy such as wind energy, solar energy, tidal energy, geothermal energy, bio-energy, etc. It combines "source-grid-load-storage" vertically and "multi-energy complementation" horizontally, coordinates centralized grid and distributed energy network and realizes synergetic development in and between energy subsystems.

3.1.1 Vertical coordination of "source-grid-load-storage"

The synergy of internal subsystems of regional integrated energy supply system is the vertical coordination of "source-grid-load-storage" where the each link follows the same evolution direction of the whole subsystem. This process does not occur separately but interacts with its structure and environment.

"Source-load" balance is demonstrated by the synergy of energy supply and demand. At the "source" end of energy supply, the resource reserve decides the exploitable volume of resource while the exploitation capability further decides the scale of energy supply; the resource distribution decides the distribution of energy supply capacity. The energy supply capacity is influenced by all these supply conditions.

"Source-grid" coordination is in essence the coordinating and matching between energy supply capacity and energy transmission and distribution capacity. At the "source" end, the progress of resource exploration capability, exploitation capability and energy production technology can gradually enlarge the capacity of energy supply; at the "grid" end, the grid construction input and technology progress can expand the capacity of transmission channel and uplift the transmission and distribution efficiency; the improvement of peak regulating capacity will also expand the transmission and distribution capacity of energy grid.

The dynamic interaction of "source-grid-load-storage" makes use of the flexible regulating feature of energy storage at the transmission/distribution end and load end and better matches energy supply, transmission/distribution and demand for synergized development. When energy supply exceeds the grid transmission capacity or consumption demand, the energy storage system may temporarily store the surplus; then it releases energy to meet demand in case of inadequate energy supply or huge upsurge of demand.

3.1.2 "Multi-energy complementation" horizontal coordination

The subsystems within the regional integrated energy supply system are interactive with mutual impact where different types of energy are coupled by CCHP for mutual complementation. Their synergized development can realize large-scale utilization and sharing of renewable energy and tighten the connection between electric power system and heat production system and fuel gas network.

Multi-energy complementation refers to the relations of mutual conversion, complementation and substitution of different types of energy. The multi-energy complementation in the regional integrated energy supply system means the coordination and complementation of different energy types including electricity, coal, heat and gas supply. It is flexibly applied in accordance with different resource conditions and energy consumers that can reasonably utilize natural resources and gain better economic, social and environmental benefits. Such mode covers the source-side integrated energy system, user-side integrated energy system and energy transmission network.

3.2 Synergetic evolution mode of integrated energy supply system

In the synergetic evolution process of energy system, the different parts of evolution have respective abilities in evolution, either higher or lower in different stages of evolution; the drive factors of evolution yield the synergetic evolution effect with different extent in different stages.

The self-synergy evolution process of each subsystem is decided by its internal factor but also influenced by external factor. These factors function on different links (levels) of subsystem, which are reflected by the evolution capability of each link and the synergetic effect on different link. From the angle of two dimensions, the synergetic evolution capability slides from high to low while the synergetic evolution effect grows from small to big, which can be displayed in four evolution quadrants that describe the synergetic evolution path of energy subsystems in accordance with the change of capability and effect. See the below figure. The four quadrants stand for the four status of energy subsystem development: disorder of subsystem, isolated development, static stagnation of subsystem and synergized development of subsystem.

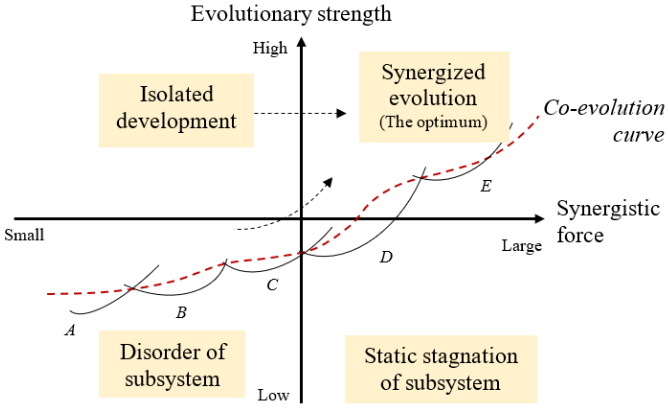

Fig 1 The self-synergy evolution process of each energy subsystem

Pursuant to the natural law and organizational evolution theory, a self-organization follows its own development regularity to automatically form an orderly structure. In other words, the self-development of various links is a process of bending upward for continuous optimization, i.e. curve A, B, C, D and E. Each link is under the effect of mutual impact. The balance of different links means the certain extent of respective evolution capability and the balance of mutual synergy effect, i.e. the intersection of two curves is the balance point of different links. When these balance points are connected, they figure out the synergetic development path of the entire subsystem, i.e. the bending upward co-evolution curve, that a dotted line shown in the fig.1 is one of the paths. The different links and balance points of different energy subsystems will result in versatile curves of synergetic development paths. But based on the synergy theory, the common feature of these curves is inclination to upper right.

Base on the dynamic evolution process of single energy system, the conceptual model of synergetic development of several energy subsystems can be established. Similar to the self-synergy of self-organization, the synergetic evolution relations among energy subsystems are also analyzed on two dimensions.

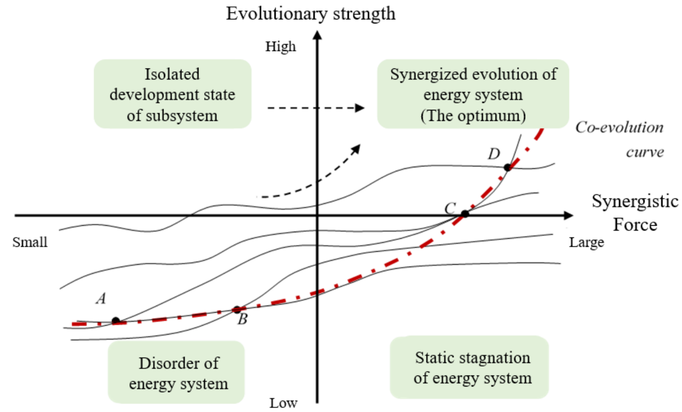

Fig 2 The synergic evolution process of integrated energy System

Different energy subsystems present the curves of different shapes of synergetic evolution paths, which may intersect when involved in one figure. The intersection of synergetic evolution curves of different subsystems demonstrate the certain extent of evolution capability of each subsystem and the balance of inter-system synergy effect, i.e. the intersection points of different curves (e.g. Point A, B, C, D and E) are the balance points of different subsystems. When these balance points are connected, they figure out the synergetic development path of the entire energy system, i.e. the bending upward co-evolution curve in the figure. It can be seen that in later stage of evolution, the synergetic evolution capability of each energy subsystem keeps improving and maintaining at a high level, and as the synergy effect of subsystems gets better, the integrated energy system gradually realizes synergized development internally.

4. EVALUATION OF SYNERGETIC DEVELOPMENT OF REGIONAL INTEGRATED ENERGY SUPPLY SYSTEM

4.1 Evaluation concept

The synergetic development level of regional integrated energy supply system refers to the status and level of regional integrated energy supply system within a specific period. The indicator system that describes its development level includes not only the indicators for each link but a few comprehensive indicators showing the development level of entire energy system.

It should be noted that the functioning of regional energy supply system is the result of joint efforts of all subsystems and their elements where some relations definitely exist between subsystems and elements. Therefore, some indicators describing the subsystem's development level may go beyond the status of single subsystem but describe the development status of several subsystems.

4.2 Evaluation indicator system and calculation method

Following the mechanism analysis of impact of regional integrated energy supply system upon the energy system and the hierarchical, scientific and measurable principles, the evaluation indicators are set up in four aspects namely basic functions, clean development, energy security and energy efficiency as shown in Table 1. Meanwhile, given the different characteristics of dimensional indicators, the specific calculation method and variable note of each indicator are provided.

Tab 1 Energy Benefit Index System

Dimensions	Indicator	Formulation	Variables
Basic Function	Level of Power Supply Facilities	$LPF_i = \frac{\sum_n PC_i^n}{\sum EL_i}$	LPF_i is level of power supply facilities in regional *i*. $\sum PC_i^n$ is total capacity of regional power supply and substation. $\sum EL_i$ is total electric load.
	Per Capita Electricity Consumption	$Per\_EC_i = \frac{TEC_i}{Pop_i}$	Per_EC_i is per capita electricity consumption. TEC_i is total regional electricity consumption. Pop_i is total regional population.
	Popularity Rate of Gas	$PRG_i = \frac{PGC_i}{Pop_i}$	PRG_i is popularity rate of gas. PGC_i is Regional Population Use of Natural Gas. Pop_i is total regional population.
	Proportion of Comprehensive Energy	$PIE_i = \frac{TIES_i}{TES_i}$	PIE_i is proportion of integrated energy. $TIES_i$ is total number of regional integrated energy station. TES_i is total number of regional substations.
Cleaner development	Proportion of Clean Energy	$PCE_i = \frac{\sum_n CEC_i^n}{\sum_n EC_i^n}$	PCE_i is proportion of clean energy. $\sum CEC_i^n$ is consumption of clean energy. $\sum EC_i^n$ is total consumption of energy.
	Clean utilization of Coal	$CUC_i = \frac{QCM_i}{QCC_i}$	CUC_i is clean utilization rate of coal. QCM_i is the quantity of clean utilization of coal. QCC_i is total consumption of coal.
	Electrification level	$EL_i = \frac{EEL_i}{TEC_i}$	EL_i is electrification level. EEL_i is electricity of electric substitution.
Energy security	Energy Self-Sufficiency	$ESS_i = \frac{\sum_n EP_i^n}{\sum_n EC_i^n}$	ESS_i is energy self-sufficiency rate. $\sum EP_i^n$ is total regional production of energy.
	Diversity of Energy	$ED_i = \sum_n \left(\frac{QEI_i^n}{\sum_n EC_i^n} \right)^2$	ED_{in} is diversity index of energy input. QEI_i^n is the quantity of type *n* energy input.
Energy Efficiency	proportion of Recovery Energy	$PRE_i = \frac{\sum_n QRE_i^n}{\sum_n EC_i^n}$	PRE_i is proportion of recovery energy. = $\sum QRE_i^n$ is quantity of recovery energy.
	Energy Intensity	$EI_i = \frac{\sum_n EC_i^n}{GDP_i}$	EI_i is Energy Intensity. Regional Total Consumption of Energy. GDP_i is regional GDP.
	Proportion of Power-to-gas	$PEG_i = \frac{QEG_i}{TGC_i}$	PEG_i is proportion of the power-to-gas. QEG_i is quantity of conversion from electricity to gas. TGC_i is regional total tonsumption of natural gas.

4.3 Evaluation methods and steps

The multi-indicator comprehensive evaluation is to turn several statistical indicators describing the different aspects and dimensions of target into the non-dimensionaluzed relative values, and summarize these values to figure out the overall evaluation of target. The prevailing evaluation methods at home and abroad include analytic hierarchy process, expert evaluation, multivariate statistical analysis, fuzzy comprehensive evaluation, etc.

The general evaluation process usually includes three steps: firstly to select evaluation indicators and set up an indicator system as per the type of subsystem; secondly to collect indicator data for normalization; thirdly to evaluate the comprehensive development level of subsystem by the selected multi-indicator evaluation method.

5. CONCLUSIONS

The thesis extends the denotation of integrated energy system and proposes the connotations and characteristics of regional integrated energy supply system. By mechanism analysis and in light with relevance analysis theory, the thesis studies all links of energy processing, conversion, transmission, storage, etc. and analyzes the synergetic development mechanism of energy system and the evolution mechanism of integrated energy supply system.

Based on the analysis of relation between energy subsystem and element, the thesis sets up the indicator system in four aspects of basic function, clean development, energy security and energy efficiency, and accordingly provides computing formula and evaluation steps. The result of study may be applied to the typical scenarios of future energy and electric power planning so as to provide a scientific tool of measuring the synergetic development level of regional integrated energy supply system. However, the thesis contains no profound analysis of specific characteristics of single energy type and its impact on the synergy of integrated energy system, which are the study orientations in the future.

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